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RESEARCH ARTICLE

Green infrastructure for species conservation: A case study of *Podarcis muralis* in Hoge Fronten, Maastricht, Netherlands

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Abstract

Urbanization poses a significant threat to biodiversity, altering habitats and ecosystems. While many species struggle to adapt, targeted conservation efforts can mitigate these impacts. This article examines the conservation of *Podarcis muralis* (wall lizard) in the Hoge Fronten, Maastricht, Netherlands. Despite the threats posed by habitat fragmentation and loss of habitat and refuges, strategic measures such as habitat restoration, artificial refuge creation, ecological corridor construction, and public engagement have facilitated a remarkable population recovery. The case study highlights the importance of integrating ecological principles into urban planning. It underscores the potential of cities to serve as havens for biodiversity when conservation is prioritized, leveraging urban ecosystems for both ecological and social benefits. This multifaceted approach offers valuable insights for managing biodiversity in urbanized landscapes and supports broader reintroduction initiatives to combat habitat loss and species decline.

Keywords

Biodiversity conservation in cities, green infrastructure, mitigation, ecological network, *Podarcis muralis,* Maastricht, the Netherlands

Introduction

Urbanization is a rapidly increasing global phenomenon that significantly impacts biodiversity and ecosystems, ranking as the second most ubiquitous threat to bio-

diversity globally, following agriculture (Chang et al., 2017). As cities expand, they exert irreversible changes on ecosystems, affecting biodiversity and ecosystem sustainability (Dong, 2019). Rapid urban expansion is predicted to have profound impacts on terrestrial vertebrate diversity globally, through habitat conversion, degradation, fragmentation, and species extinction (Li et al., 2022). These processes alter land surfaces, microclimates, habitat connectivity, ecological networks, food webs, species diversity, and species composition, underscoring the complexity of urban eco-evolutionary dynamics (Alberti et al., 2020).

Reptiles are particularly vulnerable to the impacts of urbanization. The expansion of urban areas, together with agriculture and climate change, is widely recognized as a factor impacting reptile populations (Rugiero et al., 2021). Habitat modification resulting from urban development is a key cause of reptile population declines, with variability in responses observed within and between species, families, and vegetation types (Doherty et al., 2020). Urban-adapted reptiles face an array of generalist predators in urban environments, which can vary in predation efficiency (Bateman et al., 2016). Additionally, urbanization leads to habitat fragmentation, reduces diversity, and may lead to isolation of reptile populations (Braga, Ramos, 2021). Unlike mammals and birds, most reptiles cannot easily move away from disturbances, leading to strong selective pressure to adapt to urban environments (Putman, Tippie, 2020). Research indicates that a higher proportion of reptile species are negatively affected by urbanization compared to, for example, amphibians (Hamer, McDonnell, 2010). Furthermore, noise pollution, a lesser-studied consequence of urbanization, can have detrimental effects on biodiversity, including reptiles (Sordello et al., 2020). Although generally less sensitive than mammals, lizards' hearing overlaps with mammalian sensitivity in certain frequencies, particularly in the range of 300–4000 Hz, and extends from 100 to 10,000 Hz (Christensen-Dalsgaard, Manley, 2008). Behavioral studies demonstrate that lizards respond to sound stimuli with changes in breathing patterns and can even be conditioned to react to specific sounds (Berger, 1924). Anthropogenic noise has been shown to cause stress behaviors in lizards, potentially affecting their reproductive success during critical breeding periods (Alarcon, 2015; Mayhew, 1966a, 1966b).

Despite its challenges, urban nature represents a paradox. On the one hand, urbanization disrupts natural ecosystems and intensifies human dominance over the landscape; on the other, cities often create unique ecological opportunities, fostering novel ecosystems with distinct characteristics. These ecosystems, sometimes richer in biodiversity than adjacent agricultural areas, provide valuable ecological functions and enrich urban human life (Bode, Jansen, 2017). This dynamic interplay between urbanization and biodiversity highlights the potential to integrate ecological creativity into urban planning, leveraging, sometimes changing, urban spaces for conservation (Alblas, 2024). Urban development can mitigate impacts by reducing pressures on natural landscapes and creating urban ecological niches (Onaindia, Fisher, 2020). Employing biodiversity-sensitive urban design can help maintain habitat connectivity, reduce fragmentation, and encourage public support for green space management (Tarabon et al., 2020; Fischer et al., 2020). Examples

include biophilic urban planning (Panlasigui et al., 2021) and green infrastructure, such as urban forests and corridors, which provide ecological and social benefits (Collins et al., 2017; EU, 2021). Localized good practice examples can provide valuable insights into effective conservation approaches. This article examines one such case, focusing on conservation measures for *Podarcis muralis* (wall lizard) in a city nature park in Maastricht, the Netherlands.

Podarcis muralis is protected under the Bern Convention (Appendix II), included in Annex IV of the EU Habitats Directive, and listed as Least Concern (LC) on the IUCN Red List. In the Netherlands the species is protected under Dutch national legislation (Nature Conservation Act, 2017), requiring compensatory measures for any destruction of its habitats. The species has the largest range among the genus *Podarcis* (Gasc et al., 1997; Sillero et al., 2014). Maastricht represents the northernmost natural locality of this species and is the only location in the Netherlands where it occurs naturally. Historical records suggest that the species reached this region via the east bank of the River Maas in historical times (Prick, Kruyntjens, 1992).

Podarcis muralis inhabits diverse habitats, but mostly sunlit and with less vegetation (Covaciu-Marcovet al., 2006; Žagar, 2016). It shows a high ecological plasticity that allows the colonization of different habitats, including in urban areas, often occupying secondary habitats in anthropogenic environments such as old structures, quarries, ruins, cemeteries, railway lines, etc. (Scali et al., 2015; Maletzky et al., 2011; Michaelides et al., 2013; Santos et al., 2019). However, despite its adaptability, the species remains dependent on specific habitat characteristics, and relies on a certain level of structural complexity and disarray.

In recent decades, this adaptability has facilitated significant changes in the species' distribution in the Netherlands. Recent research has documented widespread introductions, with 115 known locations by 2023, of which 20 have established sustainable populations (Spikmans, Creemers, 2024). These introductions result from both deliberate releases and accidental transport. Most introduced populations trace their origins to French (56%) and Italian (41%) lineages, raising concerns about the genetic integrity of native populations. As the Maastricht population remains the only natural one in the Netherlands, it serves as a crucial reservoir of the native genetic lineage, underscoring its conservation importance.

While *Podarcis muralis* is highly adaptable, its reliance on specific habitat conditions makes it particularly vulnerable to urbanization, which often leads to habitat degradation or loss. Urban development can compromise the structural complexity and environmental disarray the species requires, threatening its long-term survival in human-modified landscapes.

The article focuses on conservation measures undertaken for *Podarcis muralis* in Hoge Fronten, a historic urban nature park in Maastricht. These efforts not only facilitated the recovery of a declining local population but also laid the groundwork for a reintroduction project in an abandoned quarry near the city. This case study provides an overview of practical and targeted conservation strategies, offering valuable insights for biodiversity management in urbanized areas.

Materials and methods

Case study area

Maastricht, located in the southernmost part of the Netherlands, is the capital city of the province of Limburg. The case study focuses on the Hoge Fronten, part of the Bossche Fronten - remnants of 17th to 19th-century fortifications on the northwest side of Maastricht's inner city. This 15-hectare section was designated as a Protected Natural Monument (PNM) in 1992 and has been managed by the Maastricht Center for Nature and Environmental Education (Centrum voor Natuur- en Milieueducatie, CNME) (Frissen-Moors, 2020). Nowadays due to changing nature laws, the Hoge Fronten is no longer a PNM, but still is part of the National Nature Network. The Hoge Fronten's protected status is largely due to the presence of *Podarcis muralis,* whose northernmost range and only natural locality in the Netherlands is in Maastricht. Adjacent to Hoge Fronten is Lage Fronten, which also provides habitat for *Podarcis muralis* but lacks protected status (Figure 1).

Methods

The methods used in this study involved direct observations of conservation measures and comparative analysis using satellite imagery. A literature review was conducted

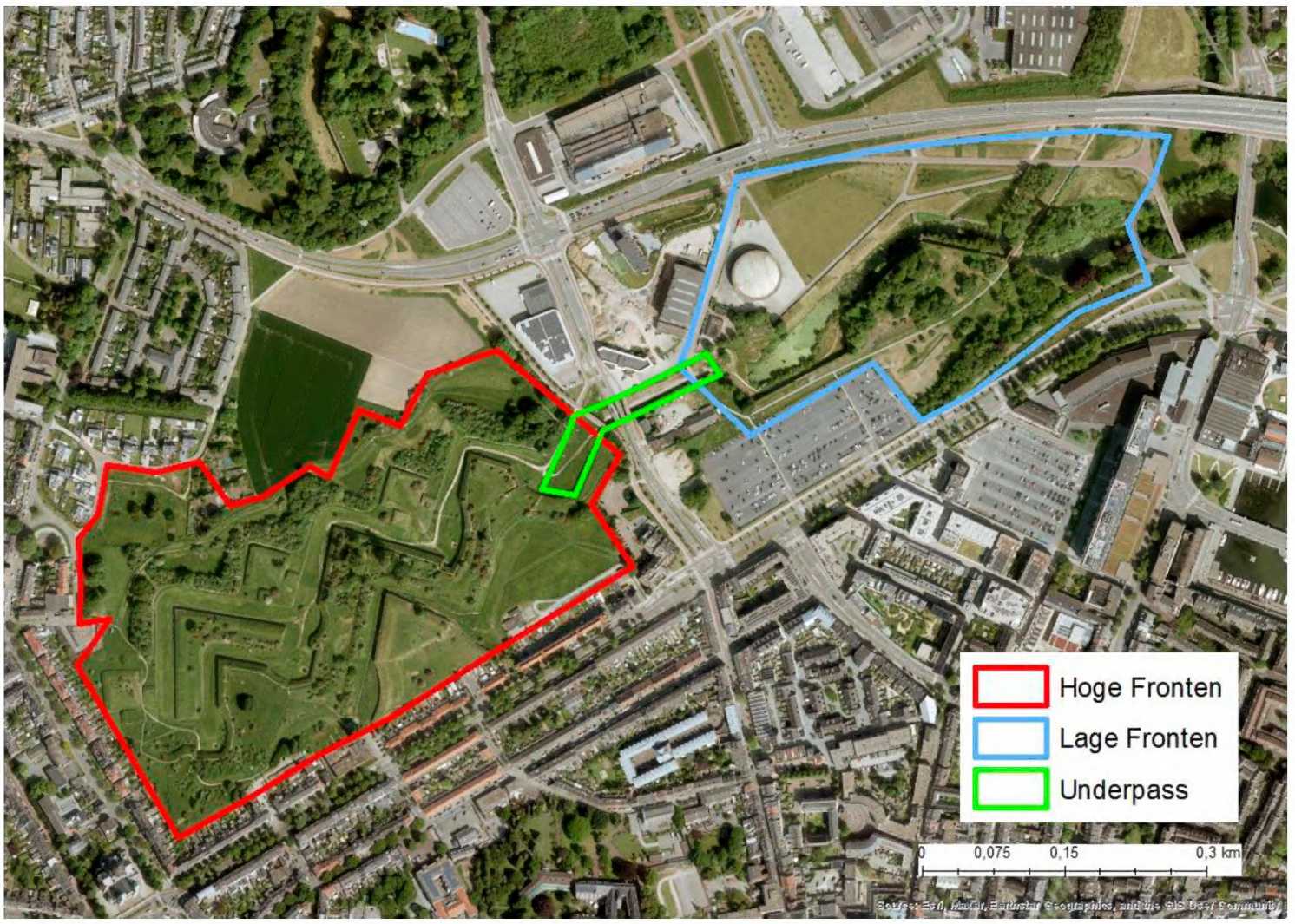

Fig. 1. Hoge Fronten, Maastricht and surrounding area

to gather data on population trends and conservation measures for *Podarcis muralis*. Field visits to the Hoge Fronten area were conducted in the period March – June 2024 to observe and document the specific measures implemented to protect *Podarcis muralis*. Observations focused on habitat modifications, such as the maintenance of fortification walls and the creation of microhabitats suitable for the lizards. The measurements of the artificial holes made in the walls for the lizards were taken using a folding rule, for 15 randomly selected holes each in the "eco wall" and in the restored walls.

Results and Discussion

The fortification walls in the Hoge Fronten provide suitable conditions for *Podarcis muralis* (Figure 2). The walls are built with marl blocks, partly protruding above ground, topped with firebrick and bluestone slabs. Some walls feature embrasures and vertical marl chains, with earthen walls behind and above the brick structures. The varied relief in the marl and surrounding vegetation allows the lizards to occupy different positions relative to the sun, helping them maintain their preferred temperature. The fortress walls, ranging from 1 to 2 meters in thickness, are often loosely stacked on the inside, providing potential overwintering spots. The marl contains winter dens that extend into self-dug holes in the earth behind the walls (Kruyntjens, 1984; Weeda, 2004).

Fig. 2. *Podarcis muralis* on the fortification walls of Hoge Fronten (photo: D. Frissen)

A survey conducted in 1979 shows that the population of *Podarcis muralis* in Maastricht consisted of about 100 adult lizards. According to the authors of the study, only good, i.e. warmer years are likely to enable a reasonable reproduction success (Strijbosch et al., 1980). In the end of 1978 in the Fronten started a restoration project (bastion Holstein-Oost, Holstein-West) executed in campaigns at several walls. As a result of rigorous earthwork and wall restorations, the population size of *Podarcis muralis* in Hoge Fronten fell to a low point in 1980 and was estimated to be 34 lizards, with only one juvenile specimen detected in the period February – November 1980. The restoration, and particularly the filling of the holes in the walls, lead to loss of refuge during the active season, and loss of wintering holes. The soil was compacted and the vegetation recovered slowly. In addition, during a restoration project in March 1983, animals were killed during their hibernation (Kruyntjens 1984, Kruyntjens 1992). Another factor negatively impacting the species has been long-term habitat fragmentation. Historically, Hoge and Lage Fronten were directly connected, forming a single unit. However, the construction of a road between them (Cabergerweg) and the subsequent heavy traffic have eliminated the chance for population exchange between these areas (Tilmans et al., 2003). According to Prick, Kruyntjens (1992) the lizards in Hoge and Lage Fronten were divided into two distinct populations, with the road likely being the primary cause of this separation.

To compensate for the negative impacts, a series of measures are taken. Refuge availability is crucial for *Podarcis muralis* in terms of thermoregulation, survival, and predator evasion strategies (Monasterio et al. 2009, Martín et al. 2010). It is essential for the survival rate and colonization (Ferreira et al. 2019). To compensate for the loss of refuges due to the restoration projects in the Hoge Fronten, new holes are bored (at first illegally) into the restored walls. The new holes, with an approximate diameter of 2 cm and a depth of 25-55 cm, increased refuge availability and facilitated lizard recolonization. The number of holes drilled varied depending on the condition of the wall from 1 hole per m^2 to 1 hole per 2 m^2 (Kruyntjens (1993). Field observations in Hoge Fronten show that the lizards actively use these new holes.

To compensate for the declining numbers of *Podarcis muralis,* breeding projects have been conducted in the Netherlands since the 1970s. A notable example of a successful breeding program began in 1989. Lizards were bred in terrariums and released in Maastricht, with 20 young lizards released in the first year of the project (Kruyntjens, 1990). Since 1992 the management of the Hoge Fronten is geared towards the sustainable maintenance and further development of the population of *Podarcis muralis* (Dienst publieke werken en sport, 1994; Kruyntjens, 1994; MLNV, 1992a, b). In 1995, the management of the area was transferred by the municipality of Maastricht to the Center for Nature and Environmental Education in Maastricht (CNME). Currently, the CNME manages nearly all the biotopes where the wall lizard is found in Maastricht, and in doing so, they have gained extensive practical experience (Op den Kamp, Frissen-Moors, 2020). The measures applied in the area include recreational zoning, tailored ecological management with special attention for the needs of the wall lizard, and awareness projects aiming to create public support.

The supervision in the area increased, reducing disruptive activities (Frissen-Moors Tilmans, 2009; Frissen-Moors, 2009; Spikmans Bosman, 2016; Frissen-Moors, 2020).

After the designation due to legislative constraints, all restorations of the fortifications are carried out in an environmentally friendly manner, with specific measures in place to protect the walls as a habitat for wall lizards. The restorations are supervised by an on-site ecologist. Efforts are made to preserve existing holes and microhabitats in and on the walls, and where that's not possible, new holes are created to maintain the lizards' habitat. Additionally, wall vegetation is preserved whenever feasible (at up to 30% of the walls), ensuring that the restoration work has minimal impact on the natural environment. If necessary, during restoration works, lizards are caught and relocated to a close, unaffected wall in the Hoge Fronten. To further protect the animals from disturbance, the access to a significant part of Hoge Fronten is limited during the spring and summer months. The population is being regularly monitored by employees and volunteers of CNME. In total, approximately 10 counts are carried out per year to make a good population estimate (CNME, 2021). The monitoring is ongoing. Data about the population numbers of *Podarcis muralis* in Hoge Fronten from the regular monitoring for the period 1977-2024 are provided at Figure 3.

In the year of designation of Hoge Fronten as PNM, the population grew to over a hundred individuals, indicating a sustainable situation (Dienst publieke werken en sport, 1994). It was no longer necessary to artificially support the population, and in 1992, the Hoge Fronten repopulation project ended. Subsequent years exhibited a significant increase in the population within the Hoge Fronten (Moors Frissen, 2004; Frissen-Moors, 2021) (Figure 3).

To mitigate the effects of habitat fragmentation, isolation, and reduced connectivity caused by urban development, comprehensive strategies are needed to restore and enhance ecological linkages. Spikmans, Bosman (2013) concluded that the implementation of a robust ecological connection between Hoge Fronten and Lage Fronten is essential. They proposed creating a reptile-friendly passage through Cabergerweg and restoring the former moat, while also considering the historical value by potentially reconstructing remnants of fortifications. In 2017 and 2018, an underpass is constructed beneath the Cabergerweg (Figure 2, Figure 4), connecting the Hoge and Lage Fronten. Part of the old moat that once linked the areas was reopened, while a new section of the moat was created. The inclusion of the underpass aligns with long-term urban development plans by the municipality of Maastricht, as part of the redevelopment of the Belvédère district. The concept was first suggested by environmental organizations approximately 25 years ago. This underpass is covered by a viaduct, which is divided into four separate structures: two viaducts for vehicular traffic and two for bicycles and pedestrians. Figure 4 shows satellite images before (April 2017) and after (September 2018) the construction of the viaduct.

Dividing the viaduct into sections is a beneficial strategy reducing shadowing for reptiles. It reduces the continuous shadow cast, allowing sunlight to reach the ground more effectively. This is particularly important for reptiles as they rely on specific temperature ranges for basking and thermoregulation. This design makes the area

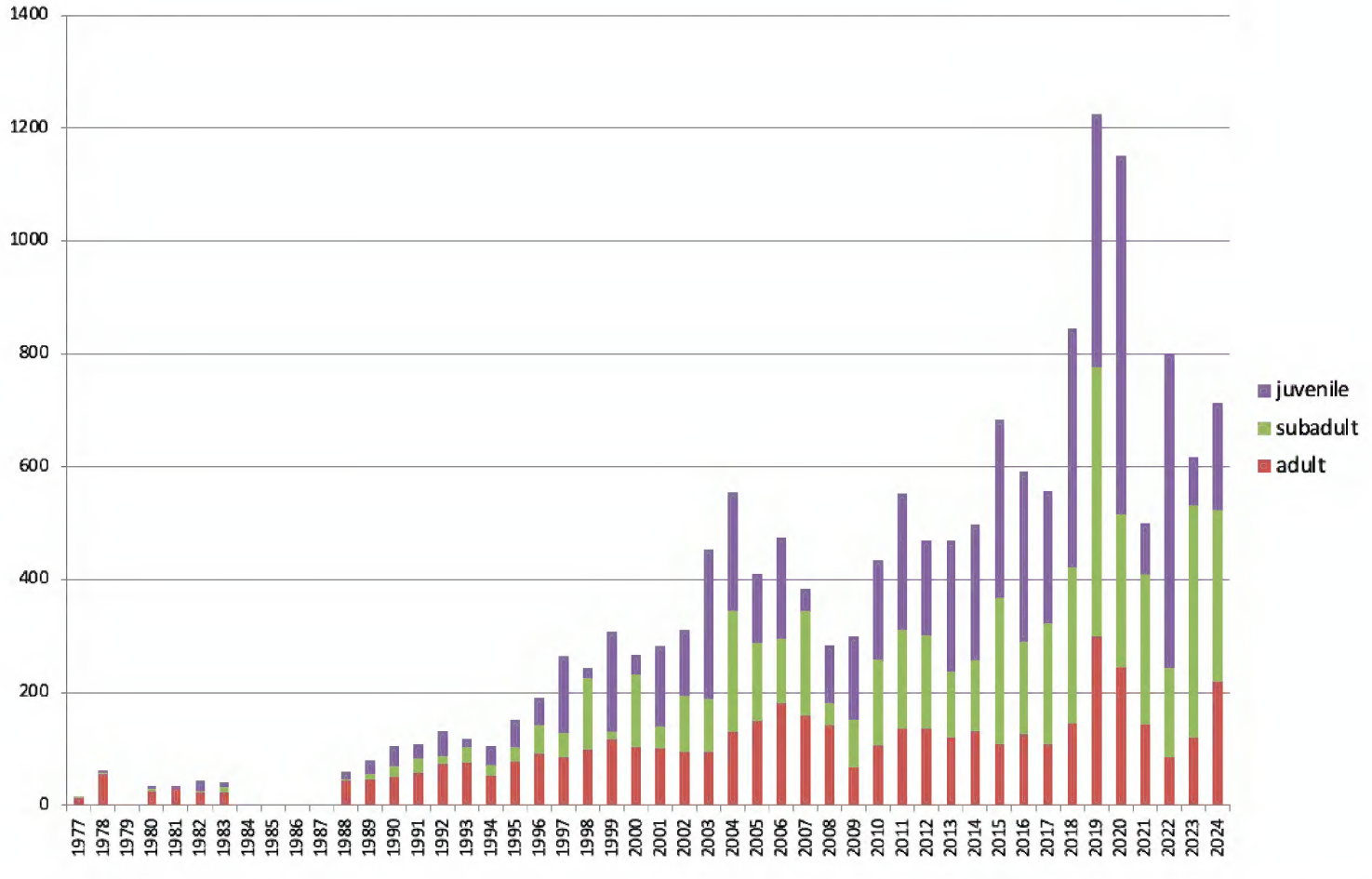

Fig. 3. Population estimate of *Podarcis muralis* at Hoge Fronten, 1977-2024 (source: CNME)

under the viaduct more suitable for the lizards and has the potential to limit both habitat loss and fragmentation.

To further mitigate the fragmentation and allow the exchange between the two populations, a 100 m long "eco-wall" was constructed between the Lage Fronten and Hoge Fronten (including under the viaducts). The bricks are staggered to facilitate movement and sun exposure/ thermoregulation of the animals. There are openings for the animals with depths between 25 and 105 cm (Figure 5).

In front of the wall (as well as at different places in the park) are placed different structures, providing additional refuges to the lizards: gabions, piles of bricks, dead trees (Figure 6).

Thanks to timely conservation measures and in the conditions of a warming climate, data from the regular monitoring (Figure 3) show that the population increased significantly, reaching over 1,200 individuals by 2019. While continued growth was expected, recent monitoring data show somewhat lower numbers in subsequent years, likely due to a combination of extreme weather conditions (particularly high rainfall) and reduced monitoring effort. However, the density of lizards on the walls remains high, and they continue to occupy marginal areas, suggesting the long-term growth trend can still be expected to continue.

The population recovery has facilitated the potential for further conservation actions, including the restoration of previously occupied habitats through the relocation of wall lizards. The growth of the population has enabled the possibility of relocating individuals to historically occupied areas, facilitating the restoration of lost

A B

Fig. 4. Cabergerweg before (A) and after (B) the construction of the viaduct (Google Earth)

Fig. 5. Eco-wall between Hoge Fronten and Lage Fronten

populations. The wall lizard reaches Maastricht via Sint-Pietersberg. Until the 1960s, it could also be found there, however, later it disappeared, probably due to the overgrowth of grasslands, forest plantings and intensive open-pit mining (Kruyntjens, 1993). By stopping industrial marl extraction in June 2020 and as a result of the intensive management, a suitable habitat for the wall lizard is developed there in the form of steep limestone cliffs and species-rich grasslands. An ongoing project, called "Towards a new stronghold for wall lizards", supported by the province, the Municipality of Maastricht and the Elisabeth Strouven Fund aims to restore the lost population in Sint-Pietersberg by relocating wall lizards from Hoge Fronten (Frissen, 2021). To ensure the project's success, a thorough preliminary study was conducted, aligned with the IUCN criteria for (re)introduction. An important argument for establishing the second population is to spread the risk in the event of a disease out-

Fig. 6. Additional structures, providing habitat to the lizards

break. The research examined the suitability of various locations on and around the Pietersberg. The 'Oehoevallei' - a part of the quarry where operations already ceased twenty years ago, has proven to be the most suitable for reintroduction (Creemers, Frissen, 2024). In May 2024 the first 50 individuals were relocated. Over the next two years monitoring of the new population will be done and more individuals will be relocated. In September 2024, the first juveniles hatched in the new habitat were observed, indicating that the relocated lizards have successfully laid and incubated eggs in the new habitat.

Conclusion

While urban development poses threats to biodiversity, there are opportunities to mitigate these impacts through strategic urban planning, public engagement, and the integration of biodiversity conservation into urban design. By recognizing the importance of biodiversity in urban areas and implementing measures to protect and enhance it, cities can strive towards sustainable development that supports both human well-being and biodiversity conservation.

The successful recovery of *Podarcis muralis* in the Hoge Fronten was achieved through a combination of habitat restoration and enhancement, which included creating and improving refuges and microhabitats, as well as breeding programs to support population growth through captive breeding and reintroductions. Efforts to mitigate habitat fragmentation were essential, reconnecting habitats through infrastructure adaptations. The designation of protected areas provided legal safeguards for critical habitats, while tailored management practices ensured the sustainability and expansion of populations. Monitoring and research offered valuable insights to guide and refine conservation efforts, and public engagement and education built awareness and

support for biodiversity conservation. This multifaceted approach demonstrates that, with the right measures and dedicated management, even nearly extinct populations can be restored, to the extent that it allows for the relocation of individuals and the restoration of other lost populations. The success in this case study highlights the potential for urban biodiversity conservation to achieve not only local recovery but also contribute to broader reintroduction initiatives in other areas.

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